Innovation in Weapons Research

Since the Laboratory's inception in 1952, our defining responsibility has been the design, development, and stewardship of nuclear weapons. This challenging mission calls for the best in science and technology. Livermore scientists and engineers respond to technical hurdles by seeking ways to "change the game," a tradition that was firmly established in the 1950s with the design of compact thermonuclear warheads that made possible ballistic missiles on submarines.

The NNSA national laboratories committed again to changing the game when nuclear testing ceased in the 1990s. Ensuring the safety, security, and reliability of an aging nuclear stockpile without underground testing demands a fundamental understanding of the physics and engineering performance of nuclear weapons. Science-based stockpile stewardship required an enormous leap in our computational and nonnuclear experimental capabilities.

The Purple supercomputer, part of NNSA's Advanced Computing and Simulation (ASC) Program, met a decade-long goal of achieving a millionfold improvement in computational power when it began operation in 2006. We are now at the threshold of being able to simulate nuclear weapon performance in great detail. ASC Purple and BlueGene/L—and in the future Sequoia—are paving the way to the use of simulations as a predictive science tool. In a similarly dramatic advance, the National Ignition Facility will provide unprecedented experimental capabilities to explore the physical processes that occur when a nuclear weapon explodes.

With these computational and experimental capabilities at our disposal, we are tackling the technical grand challenge of understanding nuclear weapon performance. We face equally formidable programmatic challenges: the nation's nuclear weapons are growing older while the nuclear weapons complex needs to become smaller, safer, more secure, and more cost effective. Livermore will provide technical leadership to NNSA to help transform the nuclear weapons complex and the stockpile. Carrying on the Laboratory's tradition, we will explore game-changing ways to meet our nation's 21st-century deterrence needs.

Bruce T. Goodwin

Principal Associate Director

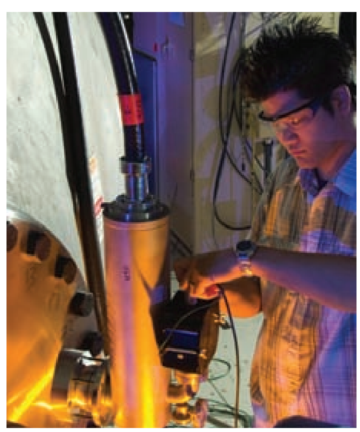
Weapons and Complex Integration

Under the National Nuclear Security Administration's draft plan to transform the nuclear weapons complex, Livermore will serve as a Center of Excellence for Nuclear Design and Engineering. Three Laboratory facilities are further identified as Centers of Excellence. The Terascale Simulation Facility (below) houses computers capable of producing high-resolution simulations of nuclear weapon behavior. The High Explosives Applications Facility (below right) and the National Ignition Facility (below far right) provide essential experimental capabilities.

Transforming the Nuclear Weapons Complex

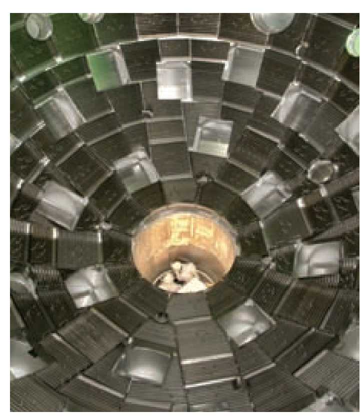
In December 2007, Tom D'Agostino, NNSA administrator, announced the release of a draft plan to transform the nation's nuclear weapons complex to make it smaller, safer, more secure, and more cost-effective. The NNSA infrastructure needs to be consolidated, made more efficient, and updated. The nation's nuclear deterrence strategy calls for a smaller stockpile, which must be maintained and modernized as needed in the face of future budgets that are expected to remain flat or decline.

The plan is described in a draft *Supplemental Programmatic Environmental Impact Statement* (SPEIS), which was issued in January 2008. The proposed transformation aims to consolidate special nuclear materials to five sites by the end of 2012. According to the plan, over the next decade, square footage will be reduced by 30 percent and the workforce directly supporting the weapons program will likely see a 20- to 30-percent reduction. Through the transformation, NNSA will eliminate duplicative facilities, reestablish a plutonium-parts production capability, speed up the dismantlement of retired weapons, and implement more efficient and uniform business practices throughout the complex.



The draft SPEIS evaluates four options to meet NNSA's goals and needs. The preferred alternative features distributed centers of excellence with a consolidation of missions and capabilities at existing NNSA sites. As a Center of Excellence for Nuclear Design and Engineering, Lawrence Livermore will retain its special responsibilities for nuclear warhead design and development, including safety, security, and reliability assessments of weapons it has designed and certification of changes made. In support of this mission, the Laboratory will conduct science and engineering research activities that underpin expertise in nuclear weapons and maintain the knowledge base so essential to sustaining the nation's nuclear weapons stockpile without nuclear tests.

Livermore will shoulder special responsibilities in three weapons research areas as part of the draft SPEIS preferred alternative. With its succession of record-breaking computers, the Laboratory will serve as a supercomputing platform host site. The Terascale Simulation Facility is currently home for two of the world's most powerful computers (see p. 8) and in the future will house the Sequoia petascale (quadrillion operations per second) machine. Livermore will also be a Center of Excellence for High Explosive Research and Development with its High Explosives Applications Facility (HEAF). HEAF is a state-of-the-art explosives research facility for formulating, processing, characterizing, and testing energetic materials. HEAF houses fully contained firing tanks for



detonating up to 10 kilograms of explosives. In addition, NIF, the world's largest laser, will serve as a center of excellence and a science magnet for high-energy-density physics research (see p. 11).

Consolidation plans also call for significant changes at the Laboratory as NNSA's nuclear weapons program is downsized. Security Category I/II amounts of special nuclear materials—plutonium and enriched uranium—are to be removed from Livermore by the end of 2012. Only Security Category III quantities of plutonium will remain for research and development activities. The inventory reduction process has already started (see p. 31). Also, hydrodynamic testing, which now takes place at the Laboratory's Site 300, will eventually transition to the Nevada Test Site. In the interim, such experimental capabilities are to be consolidated. NNSA plans to close Livermore's Contained Firing Facility (CFF) about 2015 and significantly reduce support for Site 300, where the CFF is located.

Annual Assessment of the Stockpile

Livermore is a key participant in formal review processes and assessments of the safety, security, and reliability of U.S. nuclear weapons. In 2007, the Laboratory met all milestones in support of the 12th cycle of the Annual Stockpile Assessment Process. First mandated by the U.S. president in 1995 and now required by law, the annual review includes an assessment of the current status of the stockpile. The review also gives the president an informed judgment of whether a resumption of underground nuclear testing is needed to resolve any issues about the reliability or safety of weapons. The formal process is based on technical evaluations made by Lawrence Livermore, Los Alamos, and Sandia national laboratories and on advice from the secretaries of Energy and Defense, the three laboratory directors, and the commander-in-chief of the Strategic Command.

Lawrence Livermore and Sandia-California prepare annual assessment reports for the nuclear weapons systems for which the two laboratories are jointly responsible: the W62 and W87 intercontinental ballistic missile warheads, the B83 strategic bomb, and the W80 and W84 cruise missile warheads. Laboratory scientists and engineers review and integrate all available information about each weapon system, including physics, engineering, chemistry, and materials-science data. This work is subjected to rigorous, in-depth intralaboratory review and expert external review, including formal use of red teams. Weapons experts from Livermore also provide peer review for the annual assessment reports prepared by Los Alamos and Sandia-New Mexico for the weapon systems under their joint responsibility.

Laboratory weapons experts depend on information from aboveground testing, supercomputer simulation results, stockpile surveillance data, and the existing nuclear test database to complete the annual assessment process and formal certification of refurbished or replacement warheads. This collection of data underpins the resolution of any issues arising about deployed systems. The data are also essential input for a methodology called quantification of margins and uncertainties (QMU), which scientists use to evaluate weapons performance and make decisions about refurbishing weapons or providing reliable replacements. The methodology entails the development and application of a rigorous set of metrics and is analogous to the use of engineering safety factors in designing and building a bridge. For every functional requirement, the performance margin is quantified (i.e., how far the system's performance is from failure) and compared to the uncertainty in the estimate of that margin (i.e., how uncertain are the estimates of performance and the point of failure).

A Minuteman-III intercontinental ballistic missile can carry the W87 warhead, a nuclear weapon designed by Livermore and Sandia national laboratories. Livermore met all milestones for its part in the 2007 Annual Stockpile Assessment Process.

The QMU approach benefits from the application of sophisticated statistical sampling techniques to accurately estimate the magnitude and source of uncertainties in quantitative predictions of weapon performance. This work is helping scientists determine which physics models in simulation codes are most in need of improvements and/or better input data to reduce uncertainties. QMU also helps Livermore to focus experimental programs on gathering data most relevant to measuring system performance and reducing the sources of uncertainty that can lead to system failure. In concert with continuing efforts to improve QMU, NNSA has launched an Advanced Certification Initiative to ensure that the necessary data are gathered, including more and better information from stockpile surveillance.

Design of a Reliable Replacement Warhead

In March 2007, NNSA announced the selection of the design team from Lawrence Livermore and Sandia-California to develop a Reliable Replacement Warhead (RRW)—designated WR1—for the nation's sea-based nuclear deterrent. The proposed concept combined innovation with tested features to meet all RRW goals. To develop the proposal, the Laboratory fielded a major hydrodynamics test in addition to smaller experiments, and designers ran more than 20,000 simulations to examine system trade-offs.

The goal of the RRW approach is to replace aging warheads with ones manufactured from materials that are more readily available and more environmentally benign than those used in current designs. RRWs can include advanced safety and security technologies, and they are designed to provide large performance margins for all key potential failure modes. Large margins enhance weapons reliability and help to ensure that underground nuclear testing will not be required for design certification.

After NNSA's selection of the Livermore/Sandia-California design, NNSA and the U.S. Navy began to develop a detailed WR1 project plan and cost estimate. The effort has since been halted. While seeking clarification on a number of related policy and technical issues, Congress stopped funding for RRW work in FY 2008.

Predictive Simulations for Stockpile Stewardship

ASC computers Purple and BlueGene/L, with a combined peak speed of about 700 teraflops (trillion floating-point operations per second), are being used by scientists and engineers at all three NNSA laboratories to make major contributions to stockpile stewardship. They are ushering in a new era of "predictive simulation."

Using the 100-teraflops Purple system, Laboratory scientists have gained new insights into weapon performance with simulations at unprecedented levels of resolution, revealing phenomena that had previously been hidden. The machine is being used for successive series of six-month simulation campaigns, the first of which was completed in April. October marked the end of Purple's first year as a national user facility—managed in a manner similar to a large experimental facility. Each of the three NNSA laboratories proposes computing campaigns, which aim to achieve major ASC milestones and require Purple's size and capability for at least one major calculation. The proposals are reviewed and prioritized for relevance, importance, and technical rationale. Then, machine time is allocated accordingly. Purple is the first ASC system to be managed in this way.

BlueGene/L retained its number-one spot as the world's fastest supercomputer on the Top500, which was released in November. After a recent expansion, the machine clocks an astonishing 478.2 teraflops on the industry standard LINPACK benchmark. Its peak speed is 596 teraflops. Formerly housed in 64 cabinets, the system now includes 208,000 processors in 104 cabinets. The upgrade was made to accommodate the growing demand for simulations of the most complex nuclear weapons phenomena. The expansion effort began in May. By September, scientists from Livermore and Los Alamos were running atomic-scale simulations of the ejection of fragments from shocked copper, a process that is very difficult to study experimentally.

For the third year in a row, a team from Livermore and IBM won the Gordon Bell Prize for Peak Performance for a materials-science simulation using BlueGene/L. The scientists were able to study, for the first time, how a Kelvin-Helmholtz instability develops from atomic-scale fluctuations into vortices at the scale of micrometers. The Kelvin-Helmholtz instability leads to the formation of wind-blown ocean waves, sand dunes, and swirling cloud billows. Understanding how the interactions of discrete atoms lead to seemingly continuous behavior observed at the macroscopic scale is important for stockpile stewardship and many other Laboratory programs. The innovative

computational technique that was used, which required the simulation to self-correct for routine hardware errors, could change the way high-performance scientific computing is conducted on future machines with millions of processors.

Fundamental Properties of Materials

Plutonium is arguably the most complex material known, and understanding its detailed properties is a major challenge. In 2007, Livermore researchers met an important stockpile stewardship milestone with the development of a new plutonium equation of state—a description of the state of matter under a given set of physical conditions. The new equation of state is based on advanced theory, simulations only now possible with the Purple and BlueGene/L supercomputers, and very accurate experimental data. Static experiments used a diamond anvil cell to squeeze plutonium to extremely high pressures—about 1 million atmospheres. Dynamic experiments used the two-stage gas gun at the Joint Actinide Shock Physics Experimental Research (JASPER) Facility at the Nevada Test Site. JASPER's gas gun accelerates a projectile up to 8 kilometers per second, producing on impact an extremely high-pressure shock wave in the targeted material.

Livermore scientists completed a new strength model for tantalum to meet a programmatic milestone. The model also lays the foundation for a new generation of models of material constitutive properties for use in multiphysics weapons simulation codes. Success with the tantalum stress model required combining new theoretical developments and detailed experimental measurements with modeling and simulation at several scales: quantum molecular dynamics, classical molecular dynamics, dislocation dynamics (irregularities in crystals), and macroscopic continuum physics. Developing the new strength model would not have been possible without ASC simulation tools and supercomputers. In particular, the dislocation dynamics simulations used one-third of BlueGene/L and would have taken more than 20,000 years to run using the largest computer that was available 20 years ago.

Experiments in the gas gun at the Joint Actinide Shock Physics Experimental Research Facility were important for work on a new equation of state for plutonium.

The cabinets that house BlueGene/L, the world's most powerful computer, are slanted on the front to keep cooled air flowing properly around the processors.

"Getting the Job Done" across the Weapons Complex

The Laboratory strongly supports the priorities that comprise NNSA's "Getting the Job Done" list with its ongoing stockpile stewardship activities and by assisting other sites in the nuclear weapons complex.

Livermore performs detailed peer review of the work of Los Alamos and Sandia-New Mexico on the stockpiled weapons for which they are responsible. Laboratory experts also help their colleagues to address issues as they arise. In 2007, Livermore support included fielding a large-scale hydrodynamics experiment at the CFF at Site 300. The Laboratory also aided with the resumption of pit manufacturing at Los Alamos, where a team succeeded in fabricating and certifying new pits for the W88 submarine-launched ballistic missile warheads. Livermore supplied radiographic inspection capabilities, produced small-scale plutonium samples for testing, and provided engineering evaluations and peer reviews based on a wide range of independently conducted experiments and simulations.

The Laboratory is an active participant in initiatives to significantly improve processes as well as the throughput of the nuclear weapons complex. Livermore engineers are working closely with the Pantex and Y-12 Throughput Improvement Project teams to increase plant efficiencies, expedite completion of joint projects, and introduce new capabilities. Pantex, in particular, improved dismantlement rates by more than 50 percent in 2007—significantly increasing throughput over previous years—and implemented new processes for surveillance of the W80 cruise missile warhead, a weapon for which Livermore is responsible. The Laboratory completed work with Pantex on a set of nuclear safety and weapons response issues that resulted in faster throughput by eliminating overly conservative controls in operations without compromising safety. At Y-12, technical experts from Livermore reviewed material fabrication process issues that were seriously delaying the start-up of new operations.

To help NNSA in "Getting the Job Done," researchers use the Contained Firing Facility for hydrodynamic tests, including a large-scale experiment in 2007 in support of a Los Alamos weapons program.